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APPLICATION NUMBER: *60/392,073*
FILING DATE: *June 28, 2002*
RELATED PCT APPLICATION NUMBER: *PCT/US03/20352*

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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. EL846176629US

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
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☐ *Additional inventors are being named on the ___ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

PERIPHERAL COUPLED TRAVELING WAVE ELECTRO-ABSORPTION MODULATOR

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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ENCLOSED APPLICATION PARTS ***(check all that apply)***

☒ Specification *Number of Pages* 10 ☐ CD(s), Number

☐ Drawing(s) *Number of Sheets* ☐ Other (specify)

☐ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☒ Applicant claims small entity status. See 37 CFR 1.27.

☒ A check or money order is enclosed to cover the filing fees

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FILING FEE AMOUNT ($) $80.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.

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Respectfully submitted,

SIGNATURE ____________ Date 6 / 28 / 02

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Docket Number: 0321.66619

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

This collection of information is required by 37 CFR 1.51. The information is used by the public to file (and by the PTO to process) a provisional application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the complete provisional application to the PTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, D.C. 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Box Provisional Application, Assistant Commissioner for Patents, Washington, D.C. 20231.

A. Title of Invention

Peripheral Coupled Traveling Wave Electro-absorption Modulator

B. UCSD Inventors

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We have invented the Peripheral Coupling (PC) configuration of the traveling wave electro-absorption modulation. The invention is applicable to any EA modulator, including multiple quantum well and Frantz-Keldysh modulators. It is applicable to modulators coupled to fibers or other components such as lasers. It is applicable to analog as well as digital applications. For creating a strong EA modulation over a distance of a few millimeters, this invention recognizes that only a minute amount of optical coupling between the EA material and the optical waveguide mode is desirable and necessary. It has three major benefits. (1) With weak coupling of the EA material to the optical

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waveguide, the microwave waveguide can now be designed independent of the optical waveguide. Conversely the optical waveguide can be designed independent of the EA material and microwave structure. The net result is that the optical waveguide will have extremely low insertion loss to the input and output fibers or to the laser source. The optical waveguide is easy to align with optical fibers or laser. The microwave waveguide will have reasonably high impedance, be easily driven by RF circuits or matched to other microwave circuits, be reasonably matched to the optical phase velocity, while creating effective EA effect with very low drive voltage using a very thin EA layer. In other words, our peripheral coupling configuration allows us to optimize the optical waveguide and the thin microwave waveguide separately with little interference from each other. (2) On the other hand, the Peripheral Coupling is a controlled and specifically designed, but loose, coupling configuration between the microwave waveguide that contains the EA material and the optical waveguide. There are various ways in which the Peripheral Coupling can be realized. Some of these configurations will be designed to provide special benefits such as reduction of losses. A properly designed PC modulator will have a specific length of synchronized interaction, usually millimeters long, between the optical wave and the microwave wave. In order to obtain wide bandwidth it is a traveling wave design. It utilizes the EA interaction more effectively than conventional EA modulators that are typically only a few hundred micrometers long. (3) We recognize in the Peripheral Coupled design that only a small amount of optical power in the optical waveguide is absorbed in the EA material. An important effect of the small overlap of the EA material with the optical mode is that the optical saturation power of the modulator will be much higher than other EA modulators. Large optical saturation power is important for obtaining large signal to noise ratios in optical fiber networks.

EA modulation has been in existence for some time. In conventional EA modulators, the EA material is an integral part of the optical waveguide (consequently the design of the microwave waveguide is constrained by the optical design). It is necessary to trade off optical and microwave design considerations. For example, a thin EA material will reduce the required modulation voltage, but will increase the device capacitance (making the device harder to be driven by microwave sources). An optimum optical design for coupling the waveguide efficiently to optical fibers (such as a large or diluted optical mode) will also increase either the microwave capacitance or the required modulation drive voltage. Consequently, after considering various trade-offs, existing optimized EA modulators are typically 200 μm long, or shorter, and the EA layer is a few thousand angstrom thick over the width of the waveguide. At such a short interaction length, they do not take the full advantage of traveling wave interactions. At such EA layer thickness, the drive voltage is substantial. What is unique in this invention is the Peripheral Coupling configuration that separates the microwave waveguide from the optical waveguide. Fig. 1 illustrates an example of such a configuration.

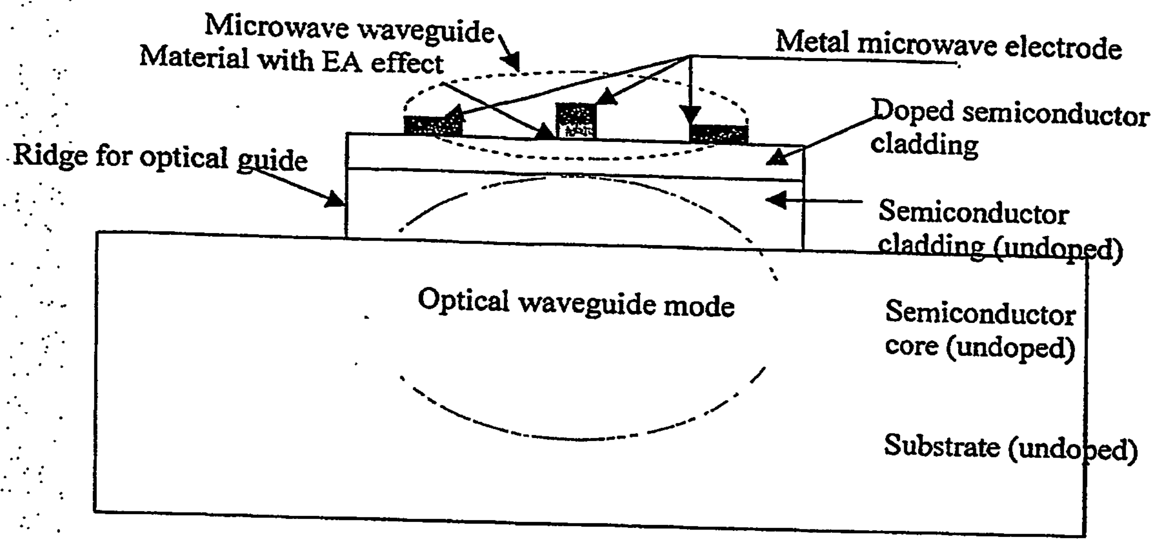


Figure 1

In this example, the optical waveguide consists of a high-index core layer sandwiched between a lower-index cladding layer and the substrate to provide vertical confinement. The lateral confinement of the optical mode is provided by the etched ridge. The transverse pattern of the optical mode is illustrated by the dotted ellipse. In order to reduce optical propagation loss, semiconductor layers for the optical waveguide are undoped or semi-insulating. The microwave transmission line consists of a coplanar micro-strip waveguide as shown by the structure highlighted by the dot-dashed ellipse in the figure. The metal electrodes and the EA material are shown. Doping of a thin layer of the cladding semiconductor below the optical ridge provides the conductivity necessary for the bottom conduction of the microstrip-like line (with a doping profile to avoid the excessive optical loss due to high surface conductivity). The microwave transmission line and the optical waveguides are only Peripherally Coupled. Since the EA layer under the center metal electrode is very thin, only a very small modulation voltage is required to create the EA effect. The micro-strip line and the center metal electrode can be very narrow, providing a reasonably high characteristic impedance and matching phase velocity. In Peripheral Coupling, the EA affects very weakly the absorption per unit propagation length of the optical wave in the optical waveguide, because the EA material is located in the evanescent tail of the optical mode. Consequently, millimeter length of propagation distance is utilized to achieve significant modulation depth. Using the traveling wave design, large modulation bandwidth can be obtained with very low modulation voltage. Such a performance is much superior than the performance of a conventional EA lumped element or traveling wave modulator.

The desirableness of a long interaction length can be viewed also from a different perspective. Any traveling wave modulator will have its best performance at very low modulation frequency, close to DC. The traveling wave design is simply intended to extend the good DC performance to high frequencies with little decay in signal frequency response. Therefore, the performance of any traveling wave modulator, except frequency response, can be evaluated first at low frequencies, or DC. At low frequency or DC, microwave capacitance, impedance, velocity and attenuation issues are not important. Without these issues, the thinner the EA layer and the longer the electrode, the less modulation voltage is required to provide the desired modulation depth.

The desired length of the electrode (i.e. the length of the modulator) is determined by the propagation loss at the bias voltage. The less the propagation loss at bias voltage, the longer the electrode and the more effective the modulation. In other words, in order to obtain the most effective modulation at DC, we will be looking for the longest practical modulator that will have a low propagation loss at the bias voltage. This can be achieved by de-coupling the EA material from the optical waveguide. The Peripheral Coupling idea includes, in addition, the advantages of both the independent designs of the optical and microwave waveguides and the acceptance of large optical intensity (i.e. large saturation optical power). Since the optical mode has evanescent field in all lateral directions, weak evanescent coupling can be accomplished with the microwave waveguide placed in many different positions, e. g. at the side instead of the center of the optical waveguide as illustrated in Fig. 1. Variation of the position of the microwave waveguide may have advantages in some considerations, such as less propagation loss of the optical mode produced by metal absorption of the optical wave, thereby allowing longer electrodes. Eventually, the length of the electrode will be limited by practical considerations such as the processing yield of long devices, the desired foot print of the packaged devices in actual applications, etc. Because of these practical reasons, we are demonstrating the invention with millimeter long devices.

From the performance point of view, in comparison with existing modulators, our invention will yield modulators that have extremely low drive voltages, large optical saturation power and very high frequency response and that can be easily driven by microwave sources.

The existing EA lumped element modulators for analog applications have typically insertion loss at zero bias , $V_\pi =$ >1.5 V, bandwidth = 40 GHz , electrode length 50 μm to 250 μm, optical saturation power ~50 mW.

From simulation, the expected performance of Peripherally Coupled traveling wave EA multiple quantum well modulators for analog applications are: $V_\pi \approx 0.27$ V at $d_i = .03$ μm., bandwidth > 40 GHz, L = 3 mm, optical saturation power > 50 mW .

An experimental material sample with intrinsic multiple quantum well EA layer on top of InGaAsP optical waveguide layers has been grown at Multiplex, Inc. In this sample, d_i = 0.1 μm. The sample has been fabricated into an optical waveguide with a peripherally coupled microwave waveguide as illustrated in Fig. 1 The optical waveguide has been evaluated. The microwave waveguide is in the process of being designed and fabricated. The EA properties of the material and the device are in the process of being evaluated. Assuming that this sample will have similar EA properties as the samples that had been grown in UCSD and that the microwave waveguide will have proper velocity match at low microwave propagation loss, we estimated the V_π to be 1.44 V at L = 1 mm. More samples and devices will be grown, designed and fabricated, to improve the performance.

Let z be the direction of propagation of the optical waveguide and the microwave waveguide. I_o is the incident optical power at the input (z=0), I (z=L) is the transmitted optical power in the optical waveguide at the output end (z = L). The microwave field in the EA material is given by the microwave voltage at z, $V_{RF}(z)$, divided by $d_{i,eff}$. For a microstrip-like microwave transmission line shown in Fig. 1, $d_{i,eff}$ is approximately the thickness of the intrinsic EA layer. The transmission function of any traveling-wave electro-absorption modulator (TWEAM) in response to a cw microwave voltage $V_{RF}\cos\omega t$ at z=0 is:

$$I(z=L)/I_o(z=0) = T = \eta_{ins}\cdot e^{-\Gamma\alpha_{bias}L}\cdot e^{-\Gamma\Delta\alpha_{eff}(\Delta F)L}$$

where

$$\Gamma = optical\ confinement\ factor\ of\ EA\ material$$

$$\eta_{ins} = insertion\ efficiency = C_{in}C_{out}\cdot(1-R)^2\cdot e^{-\alpha_o L} \qquad (1)$$

$$\Delta\alpha_{eff}L = integrated\ EA\ over\ L = \int_0^L \Delta\alpha(\Delta F(z))dz$$

$$\Delta F(z) = electric\ field\ seen\ by\ optical\ wavefront = \frac{V_{RF}}{di,eff}\cos(\omega t - \delta z)$$

$$\delta = phase\ mismatch\ of\ microwave\ \&\ optical\ wave = (n_{microwave} - n_{eff,opt})\omega / c$$

It is an EA modulator because a modulation voltage ΔF will create a $\Delta\alpha_{eff}$ that will change T. The optimization of the Δα (as that measured from the biasing voltage) by the ΔF is primarily a materials issue. It has been the concern of the research of EA modulators for some time. In addition, modulation of T is affected by L, Γ, η_{ins}, α_{bias}, δ, and $d_{i,eff}$.

When the microwave transmission line (i.e. the microwave waveguide) is perfectly impedance matched at the input and the output ends and when there is no microwave propagation loss, V_{RF} is just a constant (half of the microwave source voltage). When there are mismatches at the input and output end or attenuation, V_{RF} is a function of z that consists of attenuated forward and backward propagating waves. V_{RF} (z) has been worked out in many cases. We will also discuss the effect of microwave attenuation as it reduces the magnitude of V_{RF} as z increases from 0, without describing $V_{RF}(z)$ mathematically. The insertion efficiency consists of the coupling efficiency to the laser or the fiber at the input and the output ($C_{in}C_{out}$), the Fresnel reflections at the input and the output ($(1-R)^2$) and the optical wave residual propagation loss ($e^{-\alpha_o L}$, excluding the absorption due to the EA effect). $e^{-\Gamma\alpha_{bias}L}$ represents the reduction of the transmission T due to the EA effect of the bias voltage. At zero bias voltage, $e^{-\Gamma\alpha_{bias}L}=1$.

Equation (1) describes a modulation voltage that has a time variation of cosωt. In that case, matching of $n_{microwave}$ and $n_{optical}$ (i.e. matching of the microwave and optical phase velocities or $\delta = 0$) will yield the largest $\Delta\alpha_{eff}$ for a given $V_{RF}/d_{i,eff}$. For pulse modulation, Eqn. (1) will be modified. In that case, the matching of the optical and microwave group velocities will achieve the most effective modulation. Clearly, the most effective $\Delta\alpha_{eff}$ for a given drive voltage is obtained when there is the smallest $d_{i,eff}$, least microwave attenuation, best matching of phase and/or group microwave and optical velocities and best impedance matching of the microwave transmission line to the microwave driver.

In all existing EA modulators, the design considerations of microwave transmission lines and optical waveguides are interwoven. The resultant performance is compromised by the trade offs. For example, When a reasonably large Γ is used, a large α_{bias} or α_o would limit L to 200 µm or less. The power of Peripheral Coupling is to recognize the design freedoms that can be obtained by using configurations with exceptionally small Γ, leading to much more efficient modulators.

In digital applications, the bias voltage for the on-state is normally zero. Thus, $I_{on} = I_o T = I_o \eta_{ins}$ at the on-state. We like to maximize $C_{in}C_{out}$, minimize R and minimize α_o. The maximum L that can be used will depend on the insertion loss allowed, $C_{in}C_{out}$, R and the residual propagation loss α_o. At the off-state, the output power is I_{off},

$$I_{off}/I_{on} = extinction \quad ratio = e^{-\Gamma\Delta\alpha_{eff}(\Delta F)L} \qquad (2)$$

Therefore, the most effective modulator would have the smallest V_{RF} that must be used to achieve a given required extinction ratio. In order to accomplish this objective, (1) we look for the most sensitive $\Delta\alpha(\Delta F)$ and the largest ΓL in the optical design, plus the smallest $d_{i,eff}$ in the electrical design. (2) In order to obtain large $\Delta\alpha_{eff}$ for a given $d_{i,eff}$ and a given $\Delta\alpha(\Delta F)$, we need the best group velocity matching, the least microwave attenuation and the best matching to the driver circuit, in the microwave design. In Peripheral Coupled design, we recognize that much better overall performance can be obtained by using small Γ and large L (L will be limited by α_o). The Γ is kept as large as possible as long as the coupling configuration is sufficiently weak to achieve the

microwave objectives (very small $d_{i,eff}$, low attenuation, plus velocity and impedance matching) without affecting seriously the optical design that gives large η_{ins} and large L. It is interesting to note that, in the Peripheral Coupled design, we could move the metal electrodes to the side of optical waveguide to reduce α_o. The final result of Peripheral Coupled design is a large ΓL as well as a large $\Delta\alpha_{eff}$, using small drive voltage. According to Eqn. (2), the larger the I_o, the larger the maximum allowed L for a given required I_{on}.

(1) When the Frants Keldysh effect is used for EA, $e^{-\Gamma\Delta\alpha_{eff}L}$ will be less sensitive to optical wavelength change. A Frants-Keldysh PC TWEAM may be designed to achieve a minimum extinction ratio for a group of wavelengths in Wavelength Division Multiplexing (WDM) applications. (2) Since the PC design allows the microwave waveguide be placed on one side of the optical waveguide, other optical structures such as a periodic structure may also be added to the optical waveguide from the top to achieve the desired chirping effects.

In analog application, the modulation voltage is a small signal to the bias voltage. The criteria used to measure the link performance (with matched impedance at the input and the output) is the RF gain under a given bias condition,

$$G_{RF} = \left(I_o \cdot \eta_{ins} \cdot \partial T/\partial V \cdot \eta_{det}\right)^2 \cdot R_{in} \cdot R_{out} \qquad (3)$$

where η_{det} is the detector efficiency, V is the input RF modulation voltage, and R_{in} and R_{out} are the source and load resistance at the detector. Under a given bias condition,

$$T = \eta_{ins} \cdot e^{-\Gamma\alpha_{o}L} \cdot e^{-\Gamma L\Delta\alpha_{eff}(F_m \cos\omega t)}$$

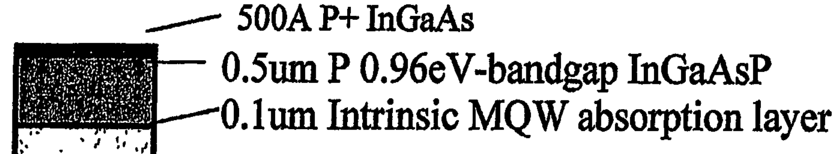
$$\partial T/\partial V_m = -\frac{\Gamma L}{d_{i,eff}}\eta_{ins} \cdot e^{-\Gamma L\alpha_{bias}} \cdot \frac{\partial\Delta\alpha_{eff}}{\partial F_m}\Big|_{bias} \qquad (4)$$

Here the modulation field in the EA material is F_m, $F_m = V_m/d_{i,eff}$. V_m is produced by the RF drive voltage V. Dependent on the α_o and α_{bias}, there is a value of optimum L that maximizes $\partial T/\partial V_m$. In addition, α and $\partial\Delta\alpha_{eff}/\partial F_m$ also vary as the bias voltage is varied. Clearly the best RF gain is obtained with the highest η_{ins}, the largest I_o, and the largest $\partial T/\partial V$. $\partial T/\partial V$ is maximized by the optimum ΓL and the smallest $d_{i,eff}$. The Peripheral Coupling allows us to use small Γ and large L to obtain the optimum ΓL. The best microwave design should yield the smallest $d_{i,eff}$ and the largest $\partial\Delta\alpha_{eff}/\partial F_m$. Since $\partial T/\partial V_m$ contains $e^{-\alpha_o L}$, the optical waveguide design should have $\alpha_o L \ll \alpha_{bias}\Gamma L$. When $\alpha_o L \ll \alpha_{bias}\Gamma L$, the maximum $\partial T/\partial V_m$ occurs approximately at $e^{-\alpha_{bias}\Gamma L} = 0.5$. At this optimum ΓL the maximum $\partial T/\partial V_m$ depends only on $d_{i,eff}$, α_{bias} and $\partial\Delta\alpha_{eff}/\partial F_m$.

Since the PC design allows high η_{ins} and large $\partial T/\partial V$, $G_{RF} > 1$ may be obtained at large [illegible]$_o$. In that case, wide bandwidth RF amplification may be achieved that cannot be obtained electronically. Such a RF amplifier could eventually be integrated on the same chip. Just like the TWEAM for digital applications, Frantz-Keldysh modulators may be used for various adjacent wavelengths with the RF gain controlled by adjustment of bias voltage.

Design of Diluted Waveguide Structure

UCSD



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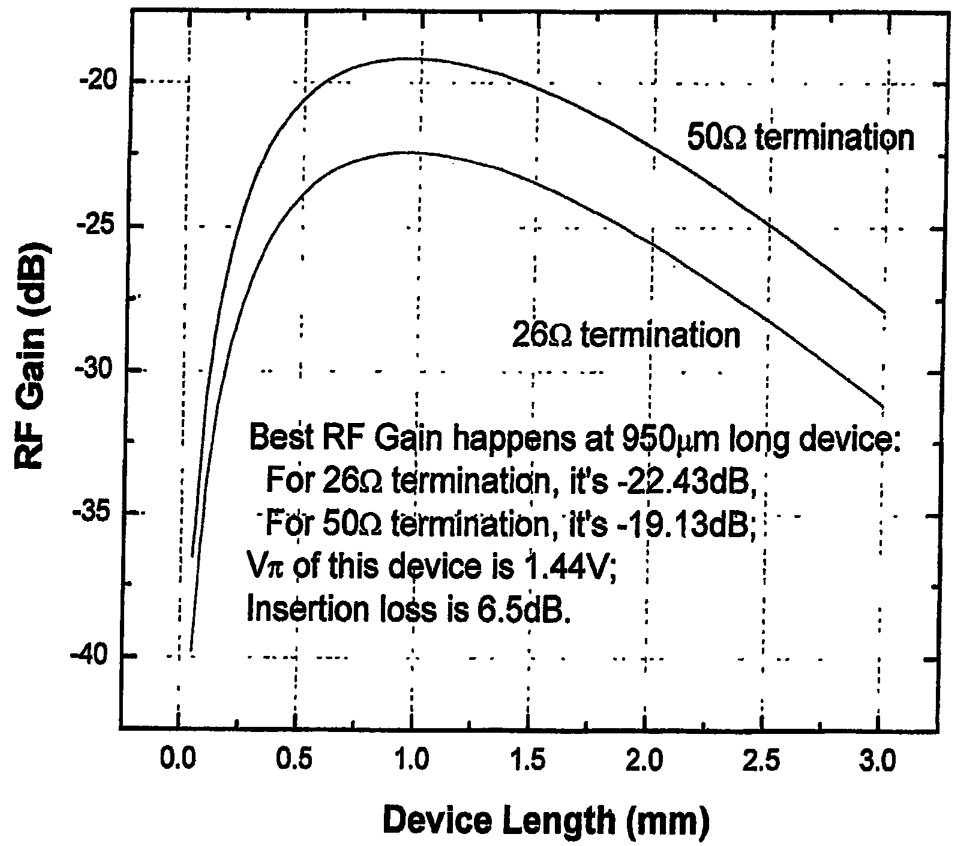
MQW sample provided by Multiplex

RF Link Gain Estimation at 10 mW



Assuming no velocity mismatch, no microwave attenuation, no impedance mismatch; V_π of 1.44 V.